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HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

FINAL REPORT 8 JANUARY 2000

Science Applications International Corporation

An Employee-Owned Company

NASA Contract NASW-5018

Space Physics Supporting Research and Technology Program (SR&T)

Dalton D. Schnack

Principal Investigator

Science Applications International Corp.

10260 Campus Point Drive

San Diego, CA 92121

Heating and Large Scale Dynamics of the Soar Corona

Final Report

This document constitutes the Final Report for Contract NASW-5018, Heating and Large Scale Dynamics of the Solar Corona. Highlights of research performed under this contract are:

- A mechanism for heating the quite solar corona by dissipation of current sheets driven by photospheric motions was quantitatively elucitated.
- A new code (TRIM) for magnetohydrodynamic (MHD) simulation using an unstructured, adaptive grid was developed.
- The TRIM code was applied to simulation of the MRX magnetic reconnection experiment at Princeton Plasma Physics laboratory.
- New models for the acceleration of the solar wind were developed.

More details of these issues can be found in the individual Quarterly Progress Reports prepared under this contract. For reference, cover pages and summary sheets submitted with these reports are attached.

SAIC-96/1072:APPAT-176

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

QUARTERLY PROGRESS REPORT:

OCTOBER–DECEMBER, 1995

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA QUARTERLY PROGRESS REPORT: OCTOBER-DECEMBER, 1995

During this period, effort was concentrated in the areas of 1) coronal heating mechanisms, and 2) unstructured adaptive grid algorithms. Progress in these areas is detailed below.

1.0 Coronal Heating Mechanisms

Studies of the Parker mechanism for coronal heating by means of topological dissipation were continued. A long computer run (approximately 50 hours of Cray Y-MP C90 time) was completed. This run used a finer grid that previous runs, sufficient to adequately resolve the dynamics of the fine scale current filaments that form during the process. It was found that magnetic reconnection events observed in previous, lower resolution runs actually consisted of multiple events, with reconnection at one current filament triggering reconnection at another. The existence of this type of "cascade" of magnetic reconnection and energy liberation events has been previously speculated, but has been calculated here for the first time. These new results are presently being analyzed, and will be incorporated into an existing draft of a paper prepared for publication in the Astrophysical Journal.

2.0 Unstructured, Adaptive Grid Calculations

Work has begun on applying a previously developed unstructured, adaptive grid MHD algorithm to problems of interest to space and solar physics. This code uses a triangular mesh to describe the solution region (which may have arbitrary shape). The density of the triangles adapts dynamically to resolve fine spatial structures as they appear in the solution.

As an initial model problem, we have applied the new code to the problem of supersonic flow over a conducting sphere with an initial imbedded dipole magnetic field. The axis of the initial dipole is aligned with the upstream flow, so that this problem is axisymmetric. As the fluid flows past the sphere it sweeps the dipole magnetic field downstream and forms a shock in front of the sphere. The grid adapts dynamically to the appearance of the shock. Cases with $\beta = 8\pi p/B^2 >> 1$ (high beta), $\beta \approx 1$ (intermediate beta), and $\beta << 1$ (low beta) have been run.

This model problem serves as an initial prototype for several problems of space and solar physics, such as three dimensional magnetospheres and coronal transients. We will begin to study these applications in the near future.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

QUARTERLY PROGRESS REPORT:

JANUARY–MARCH, 1996

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA
QUARTERLY PROGRESS REPORT: JANUARY–MARCH, 1996

During this period, effort was concentrated in the areas of 1) coronal heating mechanisms, and 2) unstructured adaptive grid algorithms. Progress in these areas is detailed below.

1.0 Coronal Heating Mechanisms

Studies of the Parker mechanism for coronal heating by means of topological dissipation were continued. The long computer run reported in the October-December 1995 Progress Report has been further analyzed. It has been determined that the cause of the disruption of current filaments may be primarily due to the coalescence instability, which is driven by the attractive force between parallel currents. These results have been incorporated into an existing draft of a paper prepared for publication in the Astrophysical Journal. This paper is presently being edited for clarity of presentation, and will be submitted shortly.

2.0 Unstructured, Adaptive Grid Calculations

Work has continued on applying a previously developed unstructured, adaptive grid MHD algorithm to problems of interest to space and solar physics. This code uses a triangular mesh to describe the solution region (which may have arbitrary shape). The density of the triangles adapts dynamically to resolve fine spatial structures as they appear in the solution.

The application of the code to flow over a spherical dipole field, as described in the October-December 1995 Progress Report, has continued. We have extended these calculations to flows not aligned with the dipole axis. This makes the problems fully three-dimensional. The tilted dipole field has been successfully implemented on the triangular grid. Initial attempts to form a model three-dimensional magnetosphere by impinging Mach 2 flow on this magnetic structure have been frustrated by numerical problems that arise in the vicinity of the flow axis. These problems occur only for three-dimensional configurations. This axis a singular point of the coordinate system and is known to cause computational problems. Solutions to this problem are known for structured, quadrilateral grids. We are attempting to extend these treatments to our unstructured, triangular grid.

We have been performing a series of tests of the dynamical mesh refinement algorithm. Several different criteria for coarsening and refinement, and several threshold parameter values, have been tried. Shocks have been successfully tracked over many thousands of time steps. Numerical problems have been observed to occur in the low density region behind shocks when the grid is coarsened. This is believed to be caused by interpolation errors. Higher order interpolation schemes are being tested.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

QUARTERLY PROGRESS REPORT:

APRIL—JUNE, 1996

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA
QUARTERLY PROGRESS REPORT: APRIL—JUNE 1996

During this period, effort was concentrated in the areas of 1) coronal heating mechanisms, and 2) unstructured adaptive grid algorithms. Progress in these areas is detailed below.

1.0 Coronal Heating Mechanisms

A paper for the Astrophysical Journal has been written and revised, and final figures are being prepared. Delays were encountered because of holidays and other commitments of co-authors. We expect final submission of this paper in the September-October time frame.

2.0 Unstructured, Adaptive Grid Calculations

Work has continued on applying a previously developed unstructured, adaptive grid MHD algorithm to problems of interest to space and solar physics. This code uses a triangular mesh to describe the solution region (which may have arbitrary shape). The density of the triangles adapts dynamically to resolve fine spatial structures as they appear in the solution.

The application of the code to flow over a spherical dipole field, as described in previous Progress Reports, has continued. As reported, we have extended these calculations to flows not aligned with the dipole axis. This makes the problems fully three-dimensional. The tilted dipole field has been successfully implemented on the triangular grid. Initial attempts to form a model three-dimensional magnetosphere by impinging Mach 2 flow on this magnetic structure have been frustrated by numerical problems that arise in the vicinity of the flow axis. These problems occur only for three-dimensional configurations. This axis a singular point of the coordinate system and is known to cause computational problems. Solutions to this problem are known for structured, quadrilateral grids. We are attempting to extend these treatments to our unstructured, triangular grid.

To this end, we have tried a series of simpler test cases in order to isolate problems in the code. We have successfully run the simple case of the advection of a uniform magnetic field with supersonic flow. The field lies in the r-ϕ plane, and the flow is along the z-axis. While this simple problem is actually 2-dimensional in Cartesian coordinates, it becomes 3-dimensional when considered in the cylindrical coordinate system of the code, and it tests the advection algorithm parallel to the $r = 0$ axis. (The uniform magnetic field becomes a purely $n = 1$ field in cylindrical coordinates.) The exact (almost trivial) solution to this problem is that the field is uniformly advected without change.

We have reproduced this solution in TRIM with no resistivity. However, problems have been noted in the definition of the axial (z) current density at the inflow boundary. These errors are a result of interpolation of magnetic field components to the boundary edge of the computational domain, and are another symptom of the interpolation problems described previously. When there is no resistivity, this error in the boundary current does not feed back into the dynamics through Ohm's law. However, when finite resistivity is included, an $n = 1$ component of the axial (z) electric field is generated, thus changing the magnetic field, and hence the dynamics, at the boundary. We continue to search for a satisfactory solution to this problem.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

4th Quarterly Progress Report: Jul—Sep 1996

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Annual Report: Oct 1995 — Sep 1996

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

4th QUARTERLY PROGRESS REPORT: JUL—SEP 1996 &

ANNUAL REPORT: OCT 1995—SEP 1996

This report serves both as a Quarterly Report for the period July-September, 1996, and Annual Report for the first year period of performance, October, 1995 to September, 1996, for NASA contract NASW-5018. During this period, progress has been made in the areas described below.

1.0 Coronal Heating Mechanisms

Studies of the Parker mechanism for coronal heating by means of topological dissipation were concluded. A long computer run (approximately 50 hours of Cray Y-MP C90 time) was completed. This run used a finer grid that previous runs, sufficient to adequately resolve the dynamics of the fine scale current filaments that form during the process. It was found that magnetic reconnection events observed in previous, lower resolution runs actually consisted of multiple events, with reconnection at one current filament triggering reconnection at another. The existence of this type of "cascade" of magnetic reconnection and energy liberation events has been previously speculated, but has been calculated here for the first time. These new results were presently being analyzed, and have been incorporated into a paper prepared for publication in the Astrophysical Journal. We expect this paper to be submitted in the near future.

2.0 Unstructured, Adaptive Grid Calculations

Work was begun on applying a previously developed unstructured, adaptive grid MHD algorithm to problems of interest to space and solar physics. This code uses a triangular mesh to describe the solution region (which may have arbitrary shape). The density of the triangles adapts dynamically to resolve fine spatial structures as they appear in the solution.

As an initial model problem, we have applied the new code to the problem of supersonic flow over a conducting sphere with an initial imbedded dipole magnetic field. The axis of the initial dipole is aligned with the upstream flow, so that this problem is axisymmetric. As the fluid flows past the sphere it sweeps the dipole magnetic field downstream and forms a shock in front of the sphere. The grid adapts dynamically to the appearance of the shock Cases with $\beta = 8\pi p/B^2 >> 1$ (high beta), $\beta \approx 1$ (intermediate beta), and $\beta << 1$ (low beta) have been run.

We extended these calculations to flows not aligned with the dipole axis. This makes the problems fully three-dimensional. The tilted dipole field was been successfully implemented on the triangular grid. Initial attempts to form a model three-dimensional magnetosphere by impinging Mach 2 flow on this magnetic structure were frustrated by numerical problems that arise in the vicinity of the flow axis. These problems occur only for three-dimensional configurations. This axis a singular point of the coordinate system and is known to cause computational problems. Solutions to this problem are known for structured, quadrilateral grids. We are attempting to extend these treatments to our unstructured, triangular grid.

We have been performing a series of tests of the dynamical mesh refinement algorithm. Several different criteria for coarsening and refinement, and several threshold parameter values, were tried. Shocks have been successfully tracked over many thousands of time steps. Numerical problems have been observed to occur in the low density region behind shocks when the grid is coarsened. This is believed to be caused by interpolation errors. Higher order interpolation schemes were tested.

We have tried a series of simpler test cases in order to isolate problems in the code. We have successfully run the simple case of the advection of a uniform magnetic field with supersonic flow. The field lies in the r-ϕ plane, and the flow is along the z-axis. While this simple problem is actually 2-dimensional in Cartesian coordinates, it becomes 3-dimensional when considered in the cylindrical coordinate system of the code, and it tests the advection algorithm parallel to the $r = 0$ axis. (The uniform magnetic field becomes a purely $n = 1$ field in cylindrical coordinates.) The exact (almost trivial) solution to this problem is that the field is uniformly advected without change.

We have reproduced this solution in TRIM with no resistivity. However, problems have been noted in the definition of the axial (z) current density at the inflow boundary. These errors are a result of interpolation of magnetic field components to the boundary edge of the computational domain, and are another symptom of the interpolation problems described previously. When there is no resistivity, this error in the boundary current does not feed back into the dynamics through Ohm's law. However, when finite resistivity is included, an $n = 1$ component of the axial (z) electric field is generated, thus changing the magnetic field, and hence the dynamics, at the boundary. We continue to search for a satisfactory solution to this problem.

3.0 Multidimensional Models of the Solar Wind

We have previously reported improved thermodynamic modeling of the two-dimensional solar wind (Mikić *et al.* 1996, *EOS Trans. AGU* **77**). In that work we improved the energy equation in our MHD model to treat the solar wind more realistically. In particular, we included thermal conduction, radiation, coronal heating, and Alfvén wave acceleration (see Withbroe 1988, *Ap. J.*, **325**, 442; Hollweg 1978, *Rev. Geophys. Space Phys.*, **16**, 689; and Habbal *et al.* 1995, *Geophys. Rev. Lett.*, **22**, 1465, for examples of one-dimensional models). We are now beginning parametric studies using this approach to better model the fast and slow solar wind streams. We have also incorporated a model of the parallel heat flux that includes the transition from collisional to collisionless regimes. Initial results of this new model will be presented at the Fall AGU Meeting.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

5th Quarterly Progress Report: Oct—Dec 1996

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

5th QUARTERLY PROGRESS REPORT:

OCTOBER-DECEMBER, 1996

This report serves both as a 5th Quarterly Report for the period October-December, 1996, for NASA contract NASW-5018. During this period, progress has been made in the areas described below.

1.0 Coronal Heating Mechanisms

Work this paper continued. In particular, new diagnostics demonstrating three-dimensional magnetic reconnection have been developed. Insights based on these diagnostics have revised our estimates for submission of the paper. New figures based on this diagnostic are being generated.

2.0 Multidimensional Models of the Solar Wind

We have previously reported improved thermodynamic modeling of the two-dimensional solar wind (Mikić *et al.* 1996, *EOS Trans. AGU* **77**). In that work we improved the energy equation in our MHD model to treat the solar wind more realistically. In particular, we included thermal conduction, radiation, coronal heating, and Alfvén wave acceleration (see Withbroe 1988, *Ap. J.*, **325**, 442; Hollweg 1978, *Rev. Geophys. Space Phys.*, **16**, 689; and Habbal *et al.* 1995, *Geophys. Rev. Lett.*, **22**, 1465, for examples of one-dimensional models). We have performed parametric studies using this approach to better model the fast and slow solar wind streams. We have also incorporated a model of the parallel heat flux that includes the transition from collisional to collisionless regimes. In this model, the collisionless heat flux is given by

$$\mathbf{q} = \frac{\alpha}{\gamma - 1} 2 n_e k T \hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \mathbf{v},$$

where $\alpha \sim 1$. The transition from the collisional model, $\mathbf{q} = -\kappa_{||} \hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T$, to the collisionless model occurs smoothly at 8 R_S. Using this new model, we have found better agreement with observational data than with previous models (see Figures 1-3). These results were presented at the Fall AGU Meeting. We will begin to incorporate this model into our 2-dimensional code.

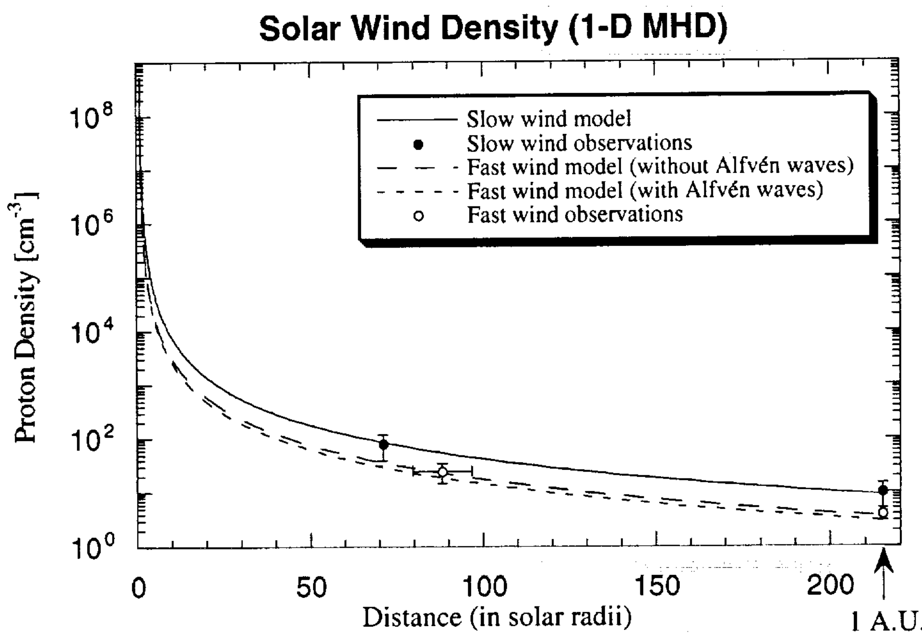

Figure 1.

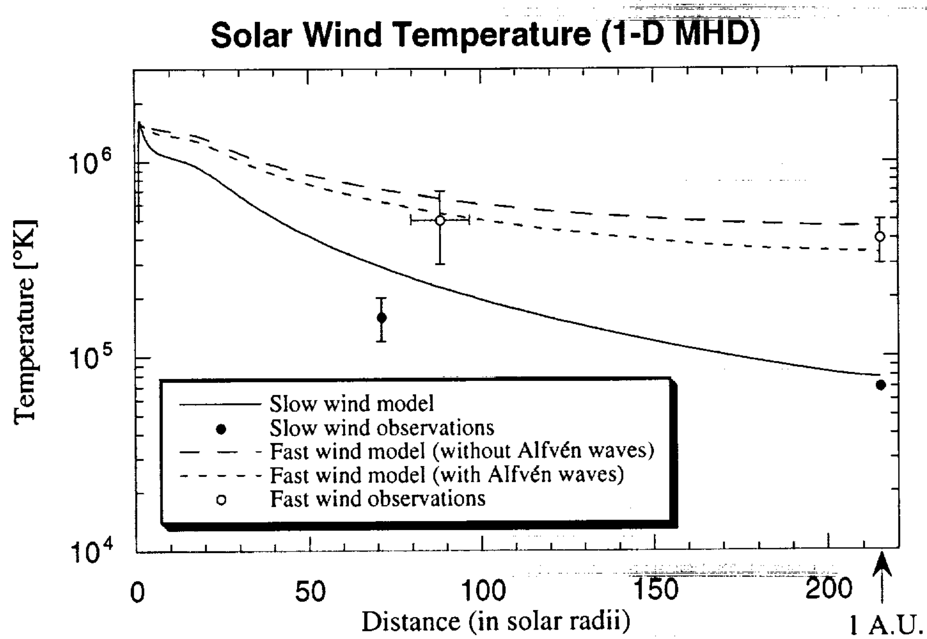

Figure 2.

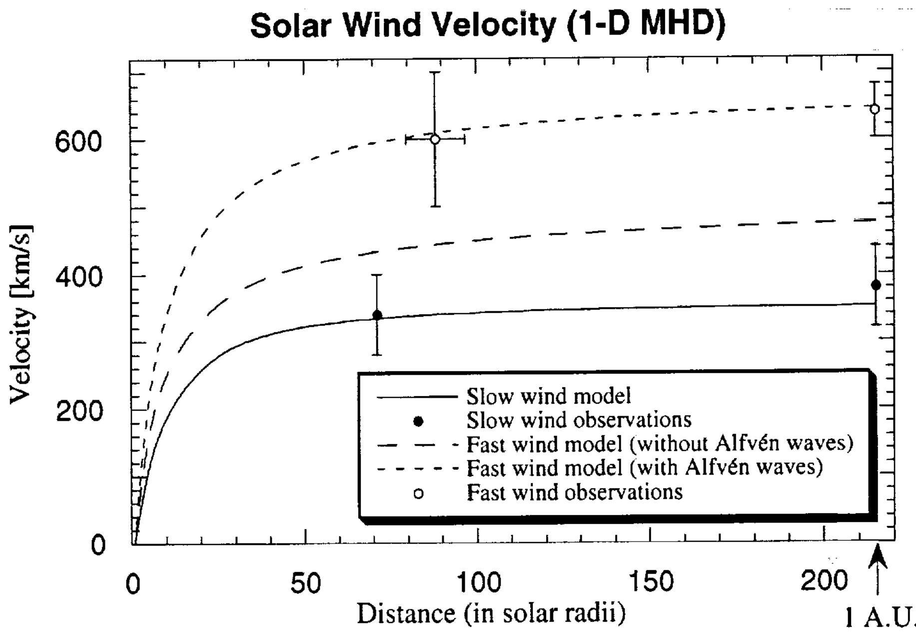
Solar Wind Velocity (1-D MHD)
Velocity [km/s]
600
400
200
0
0
50
100
150
200
Distance (in solar radii)
1 A.U.
Slow wind model
Slow wind observations
Fast wind model (without Alfvén waves)
Fast wind model (with Alfvén waves)
Fast wind observations

Figure 3.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

6th Quarterly Progress Report: Jan—Mar 1997

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

6th QUARTERLY PROGRESS REPORT:

JANUARY-MARCH, 1997

This report serves both as a 6th Quarterly Report for the period January-March, 1997, for NASA contract NASW-5018. During this period, progress has been made in the areas described below.

1.0 Unstructured, Adaptive Grid Calculations

We have begun to apply our unstructured, adaptive grid, MHD code, TRIM, to the Magnetic Reconnection Experiment (MRX) at Princeton Plasma Physics Laboratory. This experiment has been funded by NASA and NSF to study the details of magnetic reconnection in a controlled laboratory environment. Since the experiment operates in a regime where the MHD model is valid, and since the Lundquist number in MRX is a few thousand or less, this offers a unique opportunity to benchmark TRIM against real experimental results. This effort will also contribute to the success of the experimental program.

A preliminary report on our initial results is attached.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

7th Quarterly Progress Report: April–June 1997

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

7th QUARTERLY PROGRESS REPORT:

APRIL–JUNE, 1997

This report serves both as a Quarterly Report for the period April-June, 1997, for NASA contract NASW-5018. During this period, progress has been made in the areas described below.

1.0 Coronal Heating

We have finished our research on the viability of coronal heating by dissipation of thin current sheets induced by random footpoint motions, and have finalized a paper reporting these results. A copy of the paper is attached. It will be submitted to the Astrophysical Journal.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

8th Quarterly Progress Report: Jul—Sep 1997

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Annual Report: Oct 1996 — Sep 1997

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

8th QUARTERLY PROGRESS REPORT:

JULY-SEPTEMBER, 1997

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ANNUAL REPORT:

OCTOBER 1996-SEPTEMBER 1997

This report serves both as the 8th Quarterly Report for the period July-September, 1997, and as an Annual Report for the second year period of performance, October 1996-September 1997, for NASA contract NASW-5018. During this period, progress has been made in the areas described below.

1.0 Unstructured Adaptive Grid Calculations

We have begun to update the numerical algorithm in our unstructured adaptive grid MHD code, TRIM. Among the upgrades begun are: 1) the addition of an implicit algorithm for resistivity; and 2) a reformulation of the algorithm to take better advantage of the primary and dual meshes. Progress has been slowed during this period by demands from other ongoing projects.

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

9th Quarterly Progress Report: Oct - Dec 1997

NASA CONTRACT: NASW-5018

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T) PROGRAM

PRINCIPAL INVESTIGATOR:

DALTON D. SCHNACK

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

HEATING AND LARGE SCALE DYNAMICS OF THE SOLAR CORONA

9th QUARTERLY PROGRESS REPORT:

OCTOBER - DECEMBER, 1997

NUMERICAL MODELING OF MAGNETIC RECONNECTION IN THE MRX EXPERIMENT:

EFFECTS OF TOROIDAL MAGNETIC FIELD AND FINITE PRESSURE

We report continuing numerical simulations with the TRIM code[1] that are relevant to laboratory studies of magnetic reconnection in the MRX experiment[2,3] at Princeton Plasma Physics Laboratory. The MRX experiment has received support from NASA, NSF, ONR, and DOE.

As part of this contract we have previously reported initial numerical simulation of magnetic reconnection in the MRX experiment. Those calculations were limited to the force-free case with zero pressure and no toroidal magnetic field. Here we briefly report extensions of those results to cases with finite pressure and toroidal magnetic field.

1.0 EFFECT OF FINITE PRESSURE

Previously reported calculations were carried out with a force-free model. We have extended these calculations to include plasma pressure that satisfies a simple adiabatic law.. Note that the pressure builds both in the reconnection region and in the region near the flux cores where the poloidal flux is being withdrawn from the chamber. Both increases are the result of finite compressibility. The pressure increase in the reconnection region has little qualitative effect on the reconnection process. However, the increase of pressure near the flux cores is eventually sufficient to reverse the flow away from the X-point and retard the reconnection process. The combination of flow away from the flux cores and continued withdrawal of poloidal flux at the flux cores results in plasmoids forming near at the flux cores. In spite of the effect of the back pressure on reconnection dynamics, we have been able to determine the reconnection rate for a number of different values of the Lundquist number. Over this limited range, the reconnection rate scales with the Lundquist number as $S^{-0.2}$. This is to be compared with the zero-pressure result of $S^{0.3}$ reported previously. While the uncertainties in the exponent do not allow for us to discern a reliable difference between these rates, both reconnection scenarios indicate reconnection at a rate faster than the usual Sweet-Parker rate of $S^{-0.5}$.

2.0 EFFECT OF FINITE TOROIDAL FIELD

By applying a poloidal electric field at the flux core boundary, toroidal magnetic flux can be injected and removed from the chamber. By applying the same sign of voltage at each flux core, the co-helicity mode of experimental operation can be simulated.

As in the case with finite pressure and no toroidal magnetic field, the flow into and out of the reconnection region causes increases in the strength of the toroidal magnetic field both in the reconnection region and near the boundary of the flux core. As increases in toroidal flux are analogous to increases in "magnetic pressure", cases with finite toroidal field and zero pressure behave in a similar manner to those with zero toroidal field and finite pressure. In both cases the result is to retard the flow out of the X-point to a sufficient extent as to completely throttle the original magnetic reconnection process.

Not surprisingly, cases with both finite pressure and toroidal field behave qualitatively similar to the cases of zero toroidal field and finite pressure, and finite toroidal field and zero pressure.

We have not calculated reconnection rates as a function of the Lundquist number for cases with finite toroidal field.

REFERENCES

1. D. D. Schnack, I. Lottati, Z. Mikic and P. Satyanarayana, *J. Comp. Phys.* **140**, 71 (1996).
2. M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, Y. Ono, and F. Perkins, "Identification of Y-shaped and O-shaped Diffusion Region during Magnetic Reconnection", to appear in *Phys. Rev. Lett.*, April (1997).
3. M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, N. Bretz, F. Jobes, Y. Ono, and F. Perkins, "Study of driven magnetic reconnection in a laboratory plasma", to appear in *Phys. Plasmas*, May (1997).

HEATING AND DYNAMICS OF THE SOLAR CORONA

10th QUARTERLY PROGRESS REPORT:

JANUARY-MARCH, 1998

NUMERICAL MODELING OF MAGNETIC RECONNECTION IN THE MRX EXPERIMENT:

EFFECTS OF OHMIC HEATING AND VERTICAL MAGNETIC FIELD

We report continuing numerical simulations with the TRIM code[1] that are relevant to laboratory studies of magnetic reconnection in the MRX experiment[2,3] at Princeton Plasma Physics Laboratory. The MRX experiment has received support from NASA, NSF, ONR, and DOE.

As part of this contract we have previously reported numerical simulation of magnetic reconnection in the MRX experiment with both zero- and finite-pressure models. Here we report additional calculations with vertical field and Ohmic heating.

1.0 THE EFFECT OF VERTICAL FIELD

It is well known that a toroidal plasma, like MRX, will expand radially due to the interaction of its self-consistent currents and magnetic fields. This lack of equilibrium can be easily understood as arising from the mutually repulsive force provided by the anti-parallel toroidal current elements that exist at 180 degree separations in the toroidal direction. More generally, it is a result of the Virial Theorem that states that a plasma cannot be in a state of force balance due its own self-generated magnetic fields alone; external fields or conductors must be provided for equilibrium to be attained. In the MRX experiment this equilibrium is a result of both an externally applied vertical (z-directed) field, and the conducting vacuum vessel. It is easy to see that the interaction of the toroidal current with either the vertical field or the field due to the eddy currents induced in the conducting vacuum vessel provide a force that opposes the outward radial expansion of the plasma.

We have included the effect of this vertical field in our numerical simulations of magnetic reconnection in the MRX experiment. This has allowed us to better center the reconnection event between the flux cores, as is done in the experiment. No qualitative, or significant quantitative, difference between the reconnection dynamics with or without the vertical field has been observed.

2.0 EFFECT OF OHMIC HEATING

The MRX experiment obtains qualitatively different results depending on the absence of presence of a toroidal magnetic field. Without a toroidal field (null-injection), an X-point is formed in the reconnection region. With toroidal field (co-injection), the original X-point in the reconnection region is drawn into a Y-point that evolves into two X-points separated by a growing plasmoid, or secondary magnetic island. Our simulations, both with and without toroidal field, have not shown the formation of a secondary island. Rather, the reconnection always proceeds according to the classical picture with a single X-point.

It has been speculated that the secondary island may the result of Ohmic heating coupled with the inverse temperature dependence of the plasma resistivity. The toroidal current density at the X-point increases as poloidal flux is drawn into the reconnection region, with a corresponding local increase in Ohmic dissipation. As this power heats the plasma, the temperature increases and the local plasma resistivity decreases. This causes the toroidal current to increase even more near the X-point, eventually resulting in a secondary toroidal plasma, or secondary island. Of course, this toroidal plasma configuration is now subject to all the instabilities that plague toroidal pinches. In particular, it may be unstable to kink and sausage modes. These instabilities in turn may destroy the integrity of the axially symmetric secondary island, so that it will not be observed with the axially symmetric experimental diagnostics used in the MRX experiment. However, it is well known that these modes can be stabilized by a toroidal magnetic field. It is thus speculated that this stabilizing influence may account for the observed differences between the reconnection dynamics for cases with and without toroidal field; in the co-injection case the toroidal field is sufficient to stabilize the kink and sausage, or at least retard their growth to the extent that the presence of the secondary island can be detected.

We are investigating this conjecture by including Ohmic heating and Spitzer resistivity in our model. Axially symmetric calculations have been performed both with and without toroidal magnetic field. These numerical results are in good agreement with experimental measurements, but in no case has a secondary magnetic island been identified.

REFERENCES

1. D. D. Schnack, I. Lottati, Z. Mikić and P. Satyanarayana, *J. Comp. Phys.* **140**, 71 (1996).
2. M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, Y. Ono, and F. Perkins, "Identification of Y-shaped and O-shaped Diffusion Region during Magnetic Reconnection", to appear in *Phys. Rev. Lett.*, April (1997).
3. M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, N. Bretz, F. Jobes, Y. Ono, and F. Perkins, "Study of driven magnetic reconnection in a laboratory plasma", to appear in *Phys. Plasmas*, May (1997).

HEATING AND DYNAMICS OF THE SOLAR CORONA

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NUMERICAL MODELING OF MAGNETIC RECONNECTION IN THE MRX EXPERIMENT:

EFFECTS OF DYNAMIC MESH ADAPTION

We report continuing numerical simulations with the TRIM code[1] that are relevant to laboratory studies of magnetic reconnection in the MRX experiment[2,3] at Princeton Plasma Physics Laboratory. The MRX experiment has received support from NASA, NSF, ONR, and DOE.

As part of this contract we have previously reported numerical simulation of magnetic reconnection in the MRX experiment with both zero- and finite-pressure models. The effects of vertical field, Ohmic heating, and temperature dependent resistivity have also been reported. Here we report additional calculations that use dynamic mesh adaption.

1.0 THE EFFECT OF DYNAMIC MESH ADAPTION

As previously reported, the TRIM code has the capability of dynamically changing the local resolution of the grid to adapt to evolving small-scale structures in the simulation. Magnetic reconnection is a prime candidate for the application of mesh adaption because of the locally small structures that arise near the X-point.

We have repeated axially symmetric (two-dimensional) calculations of magnetic reconnection with Ohmic heating and zero toroidal magnetic field (null-injection), but with dynamic mesh adaption. There is some freedom in choosing the criterion to be used to dynamically refine and coarsen the grid. After several trials, we have found that the gradient in the axial (z-directed) velocity works well for the particular problem.

Previous results indicated that no secondary island was formed during the reconnection process. Note that, with the enhanced resolution provided by dynamic mesh adaption, the axially symmetric X-point is initially flattened and extended into two Ypoints that eventually evolve into a secondary magnetic island. Such structures are observed experimentally only in the presence of a toroidal magnetic field. It is speculated that in the absence of toroidal field these structures are unstable to three-dimensional kink and sausage modes, so they are not observed experimentally in the null-injection case calculated here. However, since our simulations were two-dimensional, the kink and sausage modes are excluded by axial symmetry. A resolution of this discrepancy between experiment and simulation awaits fully three-dimensional calculations. We plan to begin these in the near future.

We note that the execution time for these calculations was not significantly greater than with a fixed grid, but obtained results with far greater spatial resolution. In fact. the secondary island only appears with enhanced spatial accuracy. This illustrates the efficacy of direct dynamic refinement of the grid.

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